An Experimental Observation for the Shock Wave Driven by Atmospheric Microwave Plasma in a Microwave Rocket

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An experiment on microwave beaming propulsion with repetitive pulse was conducted. The microwave beaming thruster with forced breathing system was used. The forced breathing system supplies fresh air from thrust wall side into the thruster. The design flow speed in the thruster was 2.5-10m/s. A 170GHz high power gyrotron was used for microwave source. The pressure histories in the thruster were measured and propagation velocity of shock wave and thrust impulse were deduced. As a result, the velocity of shock wave in the thruster had small dependency on air flow speed because air flow speed in the thruster by forced breathing is lower than shock wave. At multi pulse operation, although at first pulse the propagation velocity of shock wave is identical to result of single pulse operation, after the second pulse propagation velocity was increased and the velocity became steady for latter pulses. As same, the impulse decrease at second pulse and steady impulse is obtained at latter pulses. Finally, the dependence of steady velocity of shock wave and thrust performance on partial filling rate of the thruster was compared to the thrust generation model with partial filling of air from the thrust wall. The experimental results on shock wave velocity and thrust impulse showed good agreement to the predicted dependency.

Nomenclature

A	=	area of thruster
a_n	=	sonic speed
C_m	=	momentum coupling coefficient
c_p	=	const pressure specific heat
f	=	pulse repetition frequency
I	=	thrust impulse
I_{single}	=	thrust impulse at single pulse operation
$L_{thruster}$	=	total length of thruster
M_n	=	Mach number
p_n	=	gas pressure
T_n	=	gas temperature
U	=	propagation velocity of shock wave and ionization front of plasma
u	=	flow velocity in the forced breathed thruster
ρ_n	=	density

I. Introduction

RECENTLY, researches on beamed energy propulsion (BEP) are held in many groups using a laser beam. Because propulsive energy is provided by beamed energy transmitted from outside, the vehicle is not necessary to load an energy source by itself and achieves high-payload ratio.[1]

In BEP, once the energy beam station is built, it can be used during many launch counts. The development cost for a beam oscillator is predominant when the launch count is few. The development cost for microwave oscillators is expected two orders of magnitude lower than that of laser, because a GW-class oscillator would be achievable by clustering existing high-power oscillators using the phased array technology. Then, microwave beaming propulsion is expected to achieve lower launch cost with fewer launch counts than laser beaming propulsion.[2]

We had conducted a single pulse experiment using a conceptual thruster with a 1MW microwave beam. The measured momentum coupling coefficient C_m, defined as a ratio of propulsive impulse to input power, was over 400N/MW.[3]

Both the plasma and the shock wave play an important role in the energy conversion process. An observation on the plasma and the shock wave in the thruster model with tube at the single pulse operation was conducted. Plasma observation with a high speed framing camera shown that ionization front of plasma propagates towards microwave radiation source at super sonic velocity in the tube. At the same time, measurement result of shock wave propagation in the tube shown that shock wave also propagated in the same velocity of plasma propagation when its velocity was supersonic. This result indicated that atmospheric millimeter-wave plasma caused isometric heating and driven a shock wave while its supersonic propagation. The thrust generation model of a microwave beaming thruster with a tube is explained in the analogy of a pulse detonation engine(PDE). In a PDE, a detonation wave starts from a thrust wall and propagates towards the exit.[4][5] In the microwave beaming thruster, a shock wave supported by the microwave plasma propagates in the tube instead of detonation wave. The shock wave makes sharp pressure increment. A rarefaction wave follows the shock wave and pressure in the tube decreases. The pressure behind the rarefaction wave is steady until the shock wave is exhausted or terminated. After the termination of the shock wave propagation, an expansion wave goes upstream from the tube exit towards the thrust wall, of which speed is sonic velocity of the constant pressure region. The pressurized air in the thruster is exhausted and pressure decreases to atmospheric pressure. In ref. 6 and 7 the thrust producing model based on shock wave propagation was proposed and pressure histories in the thruster were measured. Thrust was estimated from the pressure histories and it shown good agreement to thrust measurement by the flight experiment.[6][7]

Thrust performance under the multi pulse operation was observed at both vertical flight experiment and pressure history measurement. For the condition of 10Hz to 60Hz pulse repetition with two pulses, impulse imparted at each pulse and its C_m was deduced using the thruster model with a tube. As a result, C_m at the second pulse decreased for all the repetition conditions. References 9,10 concluded that the decrease in C_m was due to hot air remained in the thruster.[8] [9] [10]

While the microwave rocket flights at the ramjet flight mode, the fresh air is supplied from the front side of the engine and it enhances its air refilling process. However, at the ground experiment it is necessary to enhance the refreshing process for the multi pulse operation. In this study, to simulate the air breathing condition during the flight, the microwave beaming thruster with a forced breathing system which provides a fresh air from the thrust wall is designed and the behavior of the shock wave in the thruster model and its thrust performance are observed.

II. Thrust Generation Model

A thrust generation model based on the shock wave propagation in the tube style thruster with a forced breathing system is proposed. In this research, the fresh air is provided from the thrust wall side to replace the hot air remained in the thruster during the pulse interval. The fractional rate of the fresh air filling in the thruster by forced breathing depends on the parameters, the thruster length L, the pulse repetition frequency f, the bulk velocity of forced air flow in the thruster u. Thus partial filling rate of forced breathing is expressed as

$$\frac{V}{LA} = \frac{Au/f}{LA} = \frac{u}{Lf} \tag{3}$$

Figure 1 shows a schematic of a cylinder filled with the breathed fresh air and the hot air at the partial filling ratio u/Lf. Properties of the breathed fresh air are described by the subscript 0 and those of the hot remained air by subscription 0 hot. In this condition, weighted mean properties in the thruster express average properties. For example, the averaged sonic speed in the thruster a_1 is expressed as

$$a_1 = \frac{Lf/u}{\dfrac{1}{a_0} + \dfrac{Lf/u - 1}{a_{0hot}}} \tag{2}$$

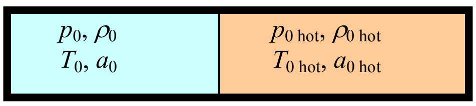

Fig.1 Partial air-filling model in the thruster

A thrust generation model based on a shock wave driving by developing atmospheric microwave plasma is explained as in Fig.2. In this experiment, as the peak microwave power density on the beam was limited to 40kW/cm^2, propagation velocity of an ionization front was subsonic.[3] Therefore, the shock wave and ionization front are detached to each other. In this case, the energy conversion process is expressed by the combination of propagation of a normal shock wave and isobaric heating at the ionization front.

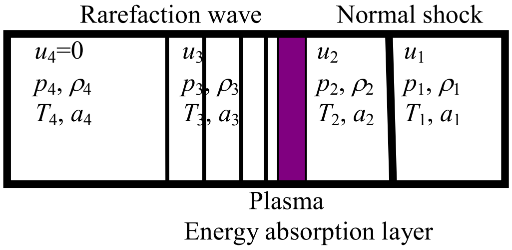

Fig. 2. Propagation of a shock wave in the thruster

The relations at each part are expressed as follows:
Normal shock relations:

$$\frac{\rho_2}{\rho_1} = \frac{u_1}{u_2} = \frac{(\gamma+1)M_1^2}{2+(\gamma-1)M_1^2} \tag{3}$$

$$\frac{p_2}{p_1} = 1 + \frac{2\gamma}{\gamma+1}\left(M_1^2 - 1\right) \tag{4}$$

$$\frac{T_2}{T_1} = \left[1 + \frac{2\gamma}{\gamma+1}\left(M_1^2 - 1\right)\right]\left[\frac{2+(\gamma-1)M_1^2}{(\gamma+1)M_1^2}\right] \tag{5}$$

Plasma region relations (isobaric heating)

$$p_2 = p_3 \qquad (6),$$

$$\rho_2 u_2 = \rho_3 u_3 \tag{7}$$

$$T_3 = T_2 + \frac{\eta S}{c_p u_2 \rho_2} \tag{8}$$

Rarefaction relations

$$\frac{p_4}{p_1} = \frac{p_3}{p_1}\left[1 - \frac{\gamma-1}{2}M_{3C}\right]^{\frac{2\gamma}{\gamma-1}} \tag{9}$$

$$M_{3C} = \frac{u_3 - u_1}{a_3} \tag{10}$$

At the pulse repetition condition, temperature at hot remained air in the thruster $T_{0\,\mathrm{hot}}$ is equal to the temperature of the exhausted air T_4:

$$T_{0hot} = T_4 \tag{11}$$

Total impulsive thrust I for a single cycle operation is calculated as,

$$I = \int (p - p_0) A dt = (p_4 - p_0) A t_{\mathrm{plateau}} \tag{12}$$

Here, A is the area of the thrust wall, and t_{plateau} is the duration time of constant pressure at the thrust wall.

III. EXPERIMENTAL APPARATUS

A. Microwave Generator

As a microwave beam generator, a high power gyrotron was used. It was developed in Japan Atomic Energy Agency (JAEA) as a microwave power source for the electron cyclotron heating and electron cyclotron current drive (ECH/ECCD) system of International Thermonuclear Experimental Reactor (ITER). Its frequency is 170GHz, and the nominal output power is up to 1MW. At the single pulse operation, the microwave pulse duration is variable from 0.1ms to CW operation and its power is almost constant during the pulse duration.[11][12]

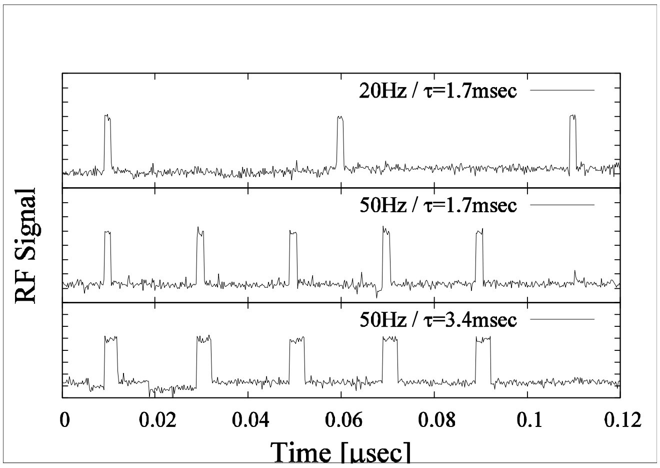

Figure 3. Typical Microwave Pulse Records

In the gyrotron, microwave is oscillated through the interaction between the accelerated electron beams and the electromagnetic waves by a cyclotron resonance maser in a cavity with magnetic fields. In this study, to provide microwave pulses repetitively, the acceleration voltage of an electron beam was modulated and the oscillation mode in the cavity was controlled. The interval time duration between pulses were settled 20ms to 50ms. A typical power history is shown in Fig.3. The pulse duration τ and peak power P of each pulse were about 1.7ms or 3.4ms and 270kW, respectively.

A microwave beam is transmitted through a corrugated waveguide to the experiment site. The output microwave beam was a fundamental Gaussian beam with a 20 mm waist.

B. Measurement Apparatus for Pressure History

A conceptual thruster model composed of a cylindrical tube with a conical nose was used as shown in Fig.4. The microwave beam was inputted from the tube exit and focused on the centerline by the conical nose reflector, initiating plasma. A shock wave and an ionization front propagate through the cylindrical tube absorbing the microwave beam during the pulse. This thruster model has the same thruster shape as that used in the flight experiment in ref. 3. The total length of the thruster was variable from 190mm to 490mm. The tube diameter was 60mm.

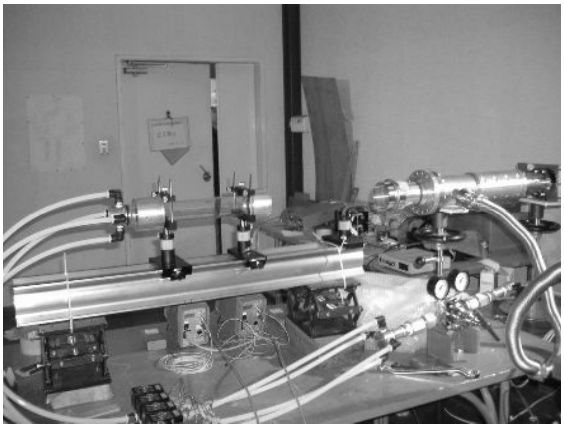
Figure 4. Picture of Thrust Measurement

To deduce the average velocity of a shock wave, pressure histories in the thruster were measured. Two flush-mount pressure gauges (Kistler's 603B) were settled at the cylindrical tube as shown in Fig.5. One is settled near the thrust wall and another is settled near the exit. The average velocity of the shock wave in the thruster was deduced from the difference of the arrival time of the shock wave at each gauge. The signal of the pressure gauges was processed using a charge amplifier (Kistler's 5011B).

To deduce the average velocity of an ionization front of the plasma, the propagation of an ionization front on the microwave beam in the thruster was also visualized using a thruster tube made of acrylic plastic and a high-speed framing camera (Photoron's FASTCAM Ultima 40K). Its frame interval was settled about 55μs.

The fresh air is supplied from the thruster wall. Four flexible tubes were connected to the conical nose and a high pressure tank. Four electric controlled valves (AB41-03-4 CKD ltd.) were settled on the flexible tubes to control the air flow in the each tube. The flow velocity of the fresh air in the thruster was controlled by the number of valves to control. Pressure at high pressure tank was kept 0.4MPa using a pressure regulator. The designed flow velocity u was varied from 2.5m/s to 10m/s.

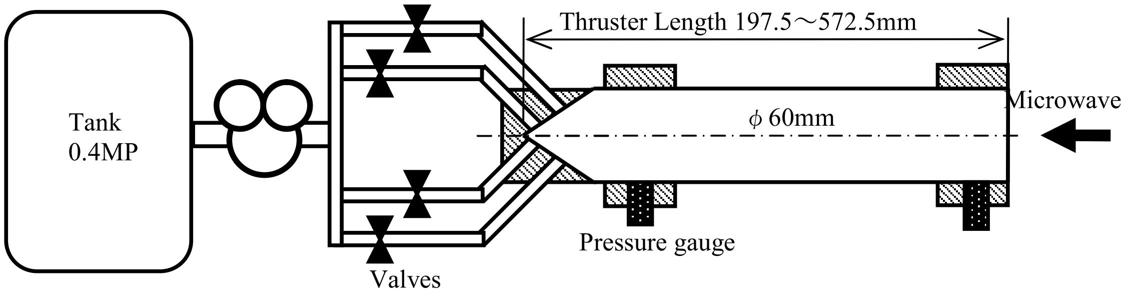

Figure 5. Thruster model with breathing system and pressure measurement

IV. EXPERIMENTAL RESULT

C. Single Pulse Operation Result

Pressure measurement and measurement of an ionization front was conducted under the single pulse operation. Figure 6 shows the pressure history near the conical nose for L=290mm thruster. After a shock wave passed at the gauge position, the pressure in the thruster shows peak and keep constant till the arrival of the expansion wave as same to the PDE model. On the other hand, Fig.7 shows the propagation of ionization front in the L=390mm thruster. The ionization front propagates at U_{plasma}=143m/s before t=1ms, after that the propagation velocity increases. This is because the velocity of the shock wave and the expansion wave are faster than the ionization front and the head of the expansion wave propagating towards the conical nose meets the ionization front during the propagation of the ionization front at t=1ms. After the expansion wave passes through the ionization front, pressure at the meeting position decrease and the velocity of the ionization front increases.

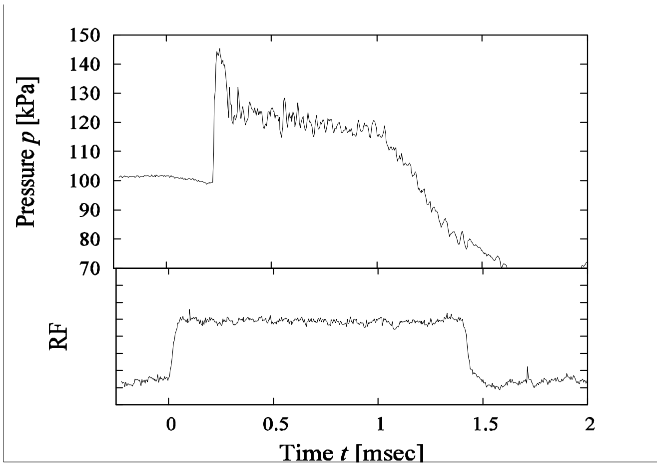

Figure 6. Typical Microwave Pulse Records L=290mm

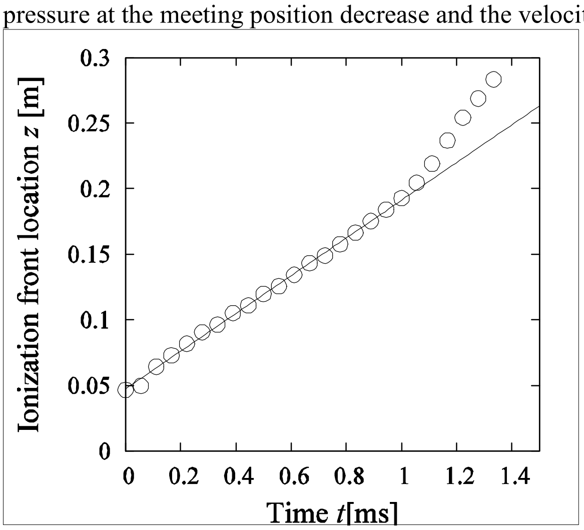

Figure 7. Propagation of the ionization front in L=390mm thruster.

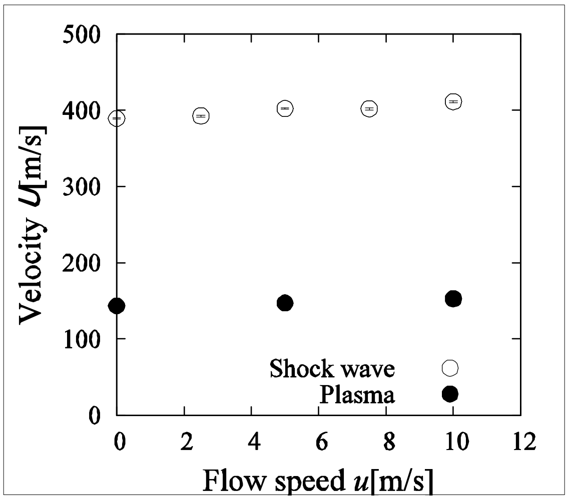

Figure 8. Dependence of shock wave and ionization front propagation velocities on air flow speed in L=390mm thruster.

To observe the effect of the forced breath system, the dependence of velocities of the shock wave and the ionization front in the thruster is plotted on Fig.8. As the speed of fresh air flow in the thruster by forced breathing is lower than the shock wave and the ionization front, the both velocities had small dependency on the air flow speed. At P=270kW, Mach number of normal shock wave was deduced as M=1.18.

D. Multi-Pulse Operation Result

The measurement under the multi pulse operation was conducted. The operation of the pulse repetition at 20Hz to 50Hz was carried out for around 0.1s duration. During the operation, 3 to 5 pulses were provided to the thruster. At each pulse, the shock wave was observed in the thruster. The velocities of a shock wave observed at each pulse input are plotted on Fig.9 and the thrust impulses are plotted on Fig.10. When the first pulse is inputted at t=0s, the propagation velocity of the shock wave was identical to the result of the single pulse operation. After the second pulse, the propagation velocity was increased and the velocity was steady for latter pulses. Therefore after the third pulse the operation is expected to be steady. The velocity U at multi pulse operation was defined the average of the velocities obtained after the third pulse.

As the same to the shock wave velocity, thrust impulse imparted at each pulse has the same dependence. The impulse decreased at the second pulse and the steady impulse was also obtained at latter pulses. At the steady operation, the average of the thrust impulses obtained at latter pulses was defined as impulse I at the multi pulse operation.

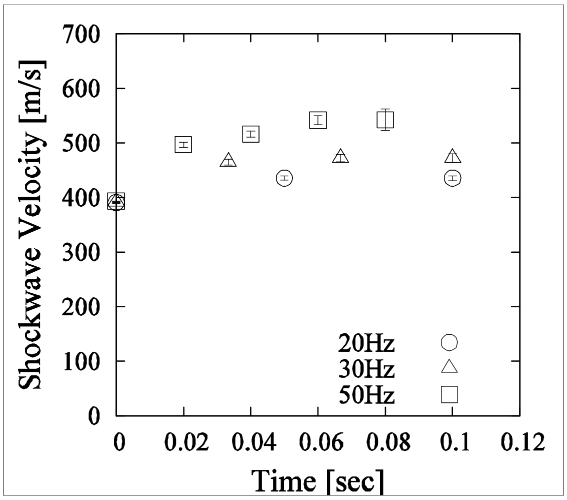

Figure 9. Dependence of the velocity of shock wave on pulse. *L*=290mm thruster

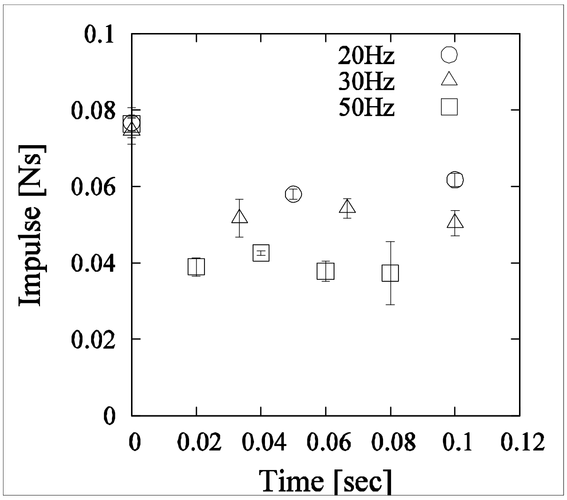

Figure 10. Dependence of thrust impulse on each pulse *L*=290mm thruster.

E. Dependence of thrust performance on partial filling rate

In the condition of the air flow velocity u=2.5m/s, the thruster length was settled L=190-490mm, and in the condition of the air flow velocity u=10m/s, the thruster length was settled L=390mm. For each condition, the average velocity of the shock wave and the imparted impulse were measured. Figure 11 shows the dependence of the shock wave velocity on the thruster length and the partial filling rate. In Fig.11, the partial filling rate u/Lf was used for horizontal-axis.

As shown in Fig. 11, the experimental results on the shock wave velocity showed good agreement to the predicted dependence by the thrust generation model based on the normal shock wave driven by atmospheric plasma under partial filling condition.

To compare the dependency of the thrust performance on the partial filling rate for difference thruster length, normalized thrust impulse was deduced because the thrust impulse obtained at each cycle depends on the thruster length. Normalized impulse I/I_{single} was defined as the ratio of the average impulse at the multi pulse operation to that at the single pulse operation. Figure 12 shows the dependence of the normalized impulse on the partial filling rate and the thruster length. In the graph, the partial filling rate u/Lf was used for the horizontal-axis.

As shown in Fig. 12, the experimental result on the thrust impulse showed good agreement to the predicted dependence as same to the shock wave.

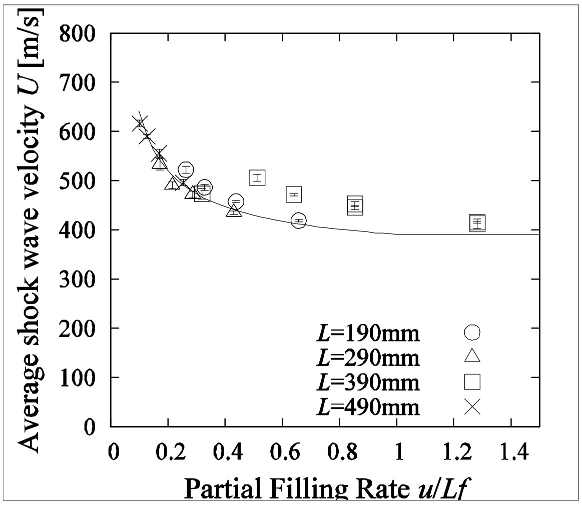

Figure 11. Dependence of average shock wave velocity on partial filling rate.

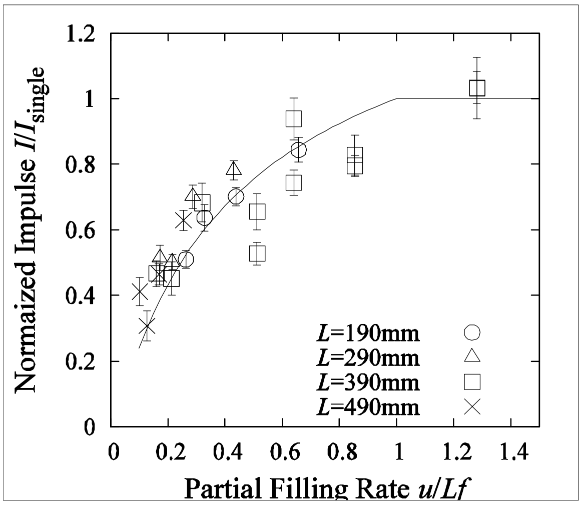

Figure 12. Dependence of normalized thrust impulse on partial filling rate.

Finally, when the partial filling rate comes unity, the normalized thrust impulse I/I_{single} become unity. This result indicates that the microwave rocket cam be operated without performance degrease under enough filling process.

V. SUMMERY

Pressure histories in the microwave beaming thruster were measured under single and multi pulse operation with the forced breathing system. The forced breathing system provides the fresh air from a conical nose into the thruster. The bulk flow speed in the thruster was 2.5-10m/s.

In the single pulse operation, the propagation velocities of the shock wave and the ionization front had weak dependency on the air flow velocity because the air flow speed in the thruster is lower than the shock wave and the ionization front.

In multi-pulse operation, the propagation velocity of the shock wave at the first pulse was identical to the result of the single pulse operation. At the second pulse, the propagation velocity was increased and the velocity was steady. At the third pulse and later, the operation became steady. As same, the impulse imparted by each pulse decreased at the second pulse and steady impulse was obtained at latter pulses.

Finally, dependencies of the shock propagation velocity and thrust performance on a partial filling rate were observed under the steady operation condition. They were compared to the thrust generation model with the partial filling of the fresh air. The measured shock propagation velocity and thrust impulse showed a good agreement with analytical predictions. When the partial filling rate is unity, the thrust impulse became identical to the thrust at the single pulse operation. This result shows that the microwave rocket can be operated without any performance degrease with perfect air-filling.

Acknowledgments

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